Searching for Dark Matter with CEvNS Detectors

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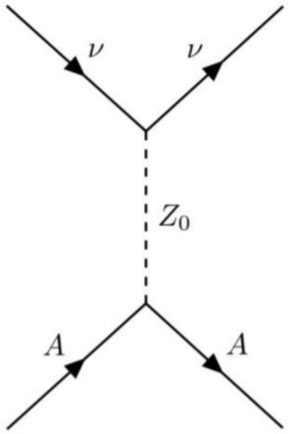
Oct 1, 2020

Snowmass NF03 Kickoff Meeting

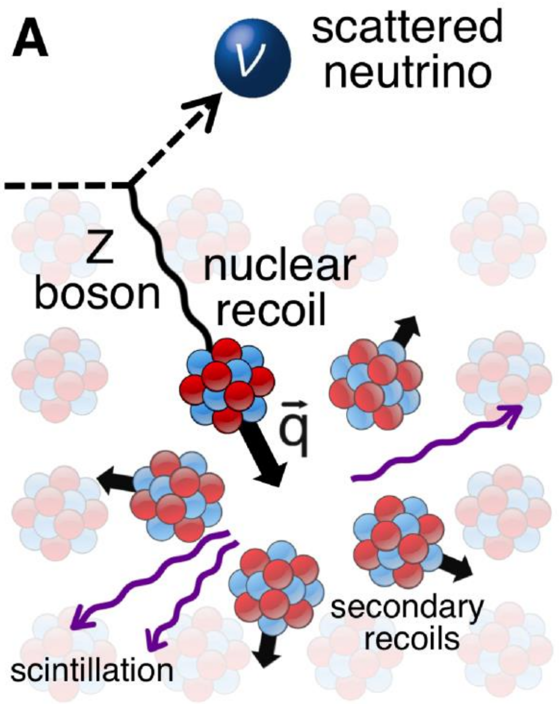
For in depth discussion, see
PhysRev **D102** 052007 (2020)

Coherent Elastic ν-Nucleus Scattering (CEvNS)



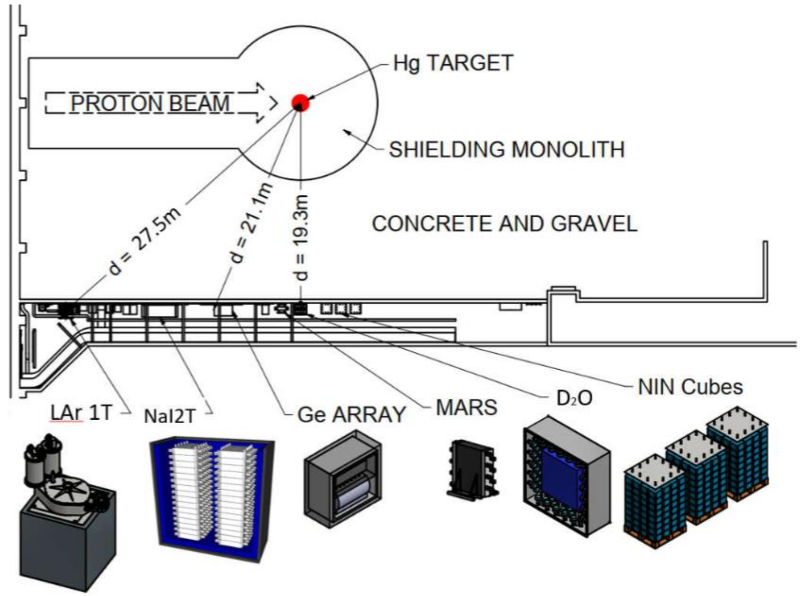
- At low Q^2, a neutrino may interact with an atom whose nucleons recoil in-phase
  - Quantum coherence increases the cross section: $\sigma \propto N^2$
  - Precisely predicted in the standard model
  - CEvNS itself is a rich probe of BSM physics

- Experimental signature is a low-energy nuclear recoil
- Need low-threshold detectors
- Need high-flux of low-energy neutrinos



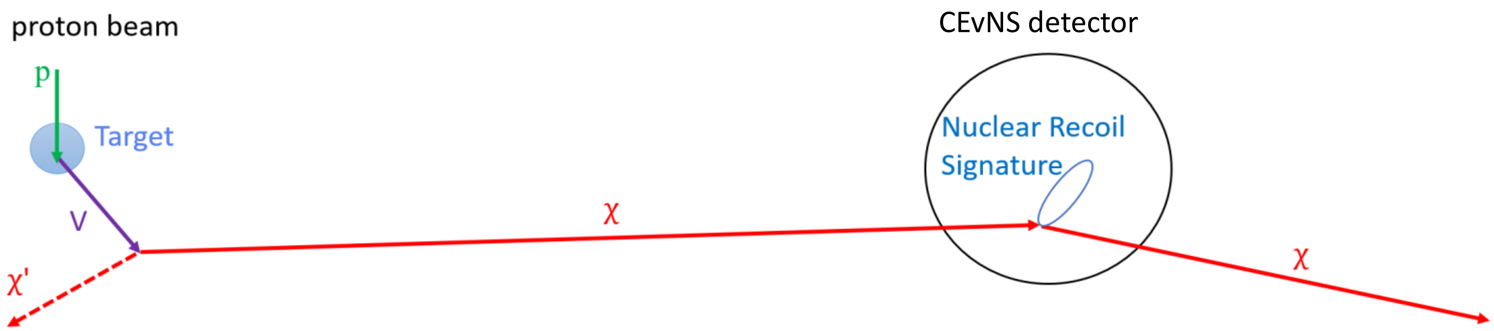
The COHERENT Experiment

Layout of COHERENT detectors in Neutrino Alley



- ❑ Uses high flux π-DAR neutrino flux from Spallation Neutron Source at ORNL
- ❑ Basement hallway "Neutrino Alley" identified as sufficiently neutron-quiet to study CEvNS
- ❑ Ongoing effort to measure CEvNS on several atoms
  - CsI: Science 357 (2017) 6356, 1123-1126 (first CEvNS detection!)
  - Ar: arXiv 2003.10630
  - Funded future detectors to study CEvNS on Ge and Na

Dark Matter at Spallation Sources



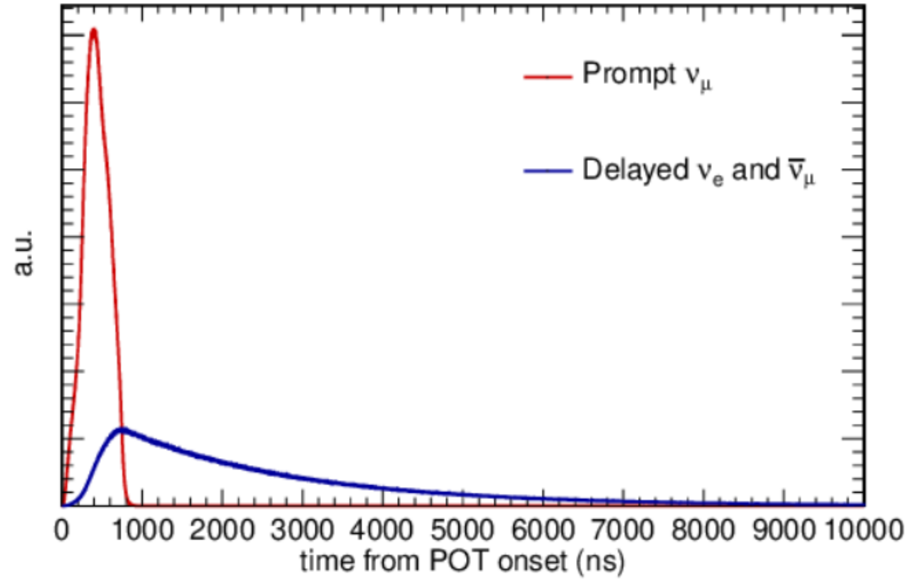
- Huge number of proton collisions in target may produce portal particles (V) that mediate interactions between SM and hidden sector particles (χ)

Benchmark Model: $\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\kappa}{2}V^{\mu\nu}F_{\mu\nu}$

E.g., deNiverville et al., Phys Rev **D92** 095005 (2015)

- Predicted χ is a viable WIMP candidate for masses below 1 GeV/c^2
- Introduces two additional couplings: ε^2 from kinematic mixing with photon and α' from $V\chi\chi$ vertex (analogous to α_{em})
- The cosmologically observed dark matter flux is proportional to a simple combination of model parameters: $Y = \varepsilon^2\alpha'\left(\frac{m_\chi}{m_V}\right)^4$

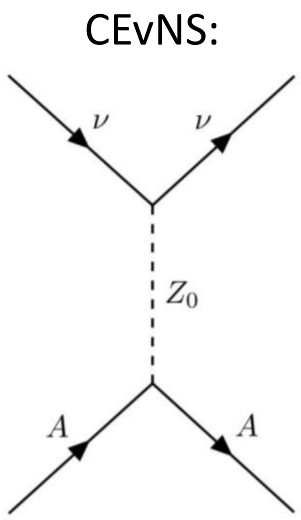
Neutrino Timing at the SNS

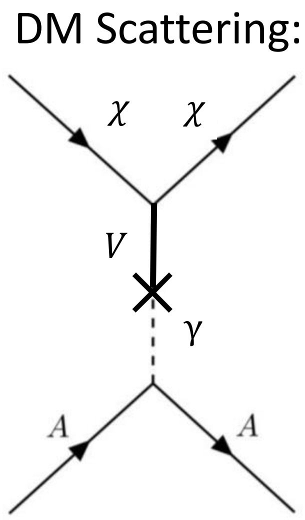


- In a π-DAR beam, neutrinos are produced from pion and muon decays
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$ – τ = 26 ns
  - $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ – τ = 2200 ns
- SNS beam is 340 ns FWHM, much larger than τ_π and much less than τ_μ
  - Neutrino flux sum of “prompt” ν_μ and “delayed” $\nu_e + \bar{\nu}_\mu$
  - DM would be relativistic, created from V decay in flight, and coincident with prompt flux

See Dutta et al., PRL 124 121802

DM Scattering in CEvNS Detectors





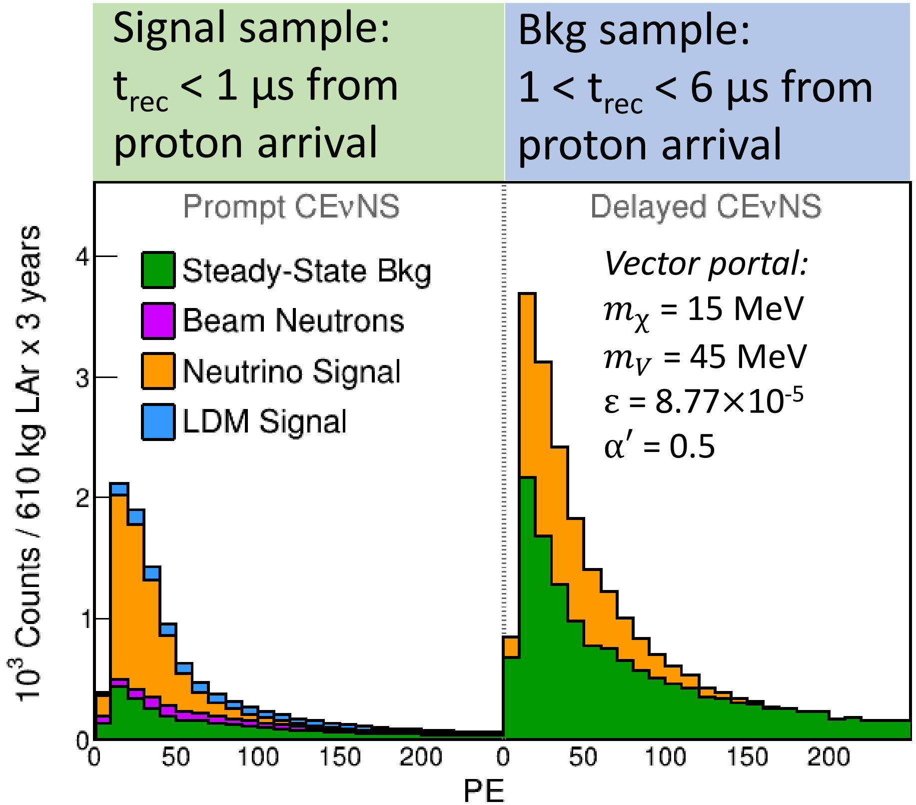
- Detectors with a low-enough threshold to observe CEvNS would also be sensitive to coherent $\chi - A$ scattering
- The cross section is similarly large and precisely calculable so that a dark matter detector sensitive to CEvNS may be competitive with much larger experiments

Nuclear Recoil Detection with Liquid Argon

- Liquid argon is a favorable detection material for dark matter searches
  - Experience within the collaboration with argon prototype detector
  - High light yield gives a threshold around 20 keV_{nr}
  - Background mitigation through efficiency pulse-shape discrimination
  - Use of underground argon significantly reduces beam-unrelated background
  - Scalability

- A ton-scale argon scintillation calorimeter in Neutrino Alley would improve on current DM constraints supplementing CEvNS physics goals
- A second, roughly 10 t, on-axis detector would aggressively constrain DM models, broadly probing parameter space consistent with the cosmological DM concentration

Detecting DM Scatters in Liquid Argon



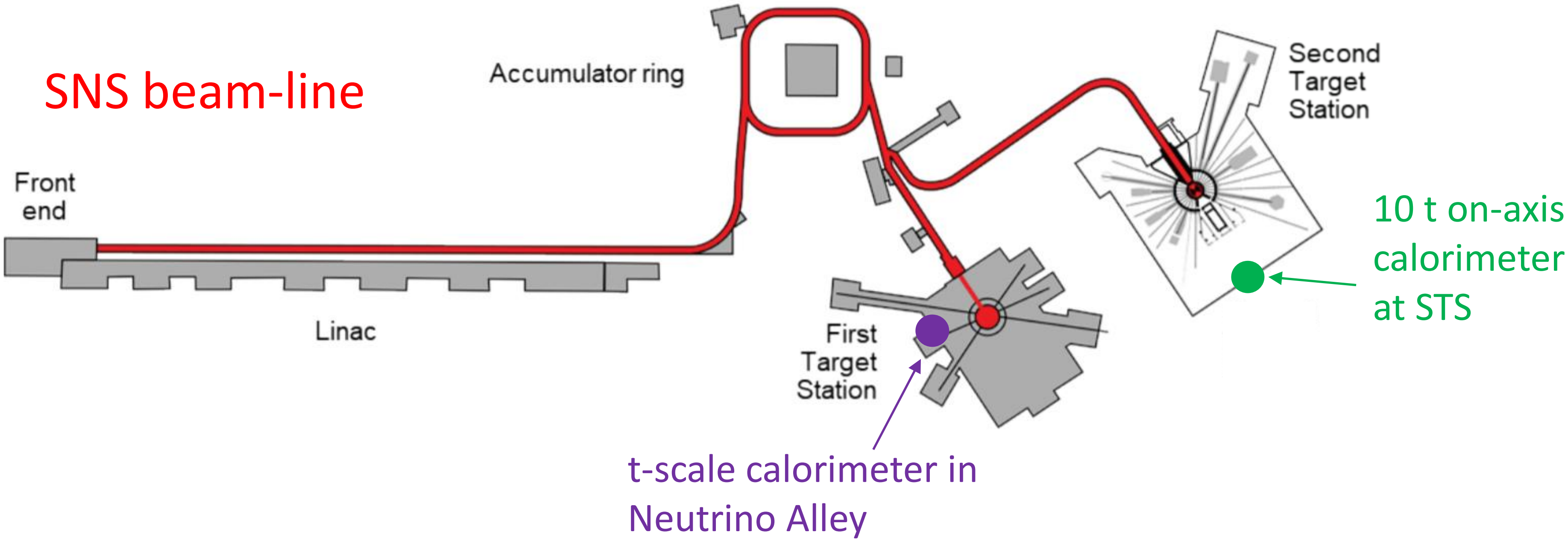
Prompt events after 610 kg x 3 yrs

Steady-state Bkg†	2790
Beam Neutrons	971
CEvNS	5469
DM	1501

†Assuming underground argon

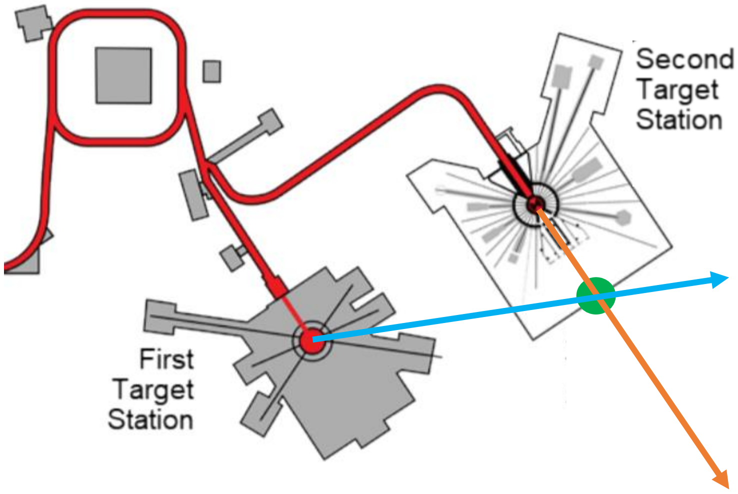
- DM sample distinguishable from backgrounds using time and energy
  - DM spectrum extends to higher recoil energies than CEvNS distribution
  - DM particles are relativistic, scatter within the prompt window (0 < t_{rec} < 1 µs) coincident with proton arrival at the target
  - Delayed window (1 < t_{rec} < 6 µs) gives in-situ measurement of neutrino bkg and is a strong constraint of systematic uncertainty

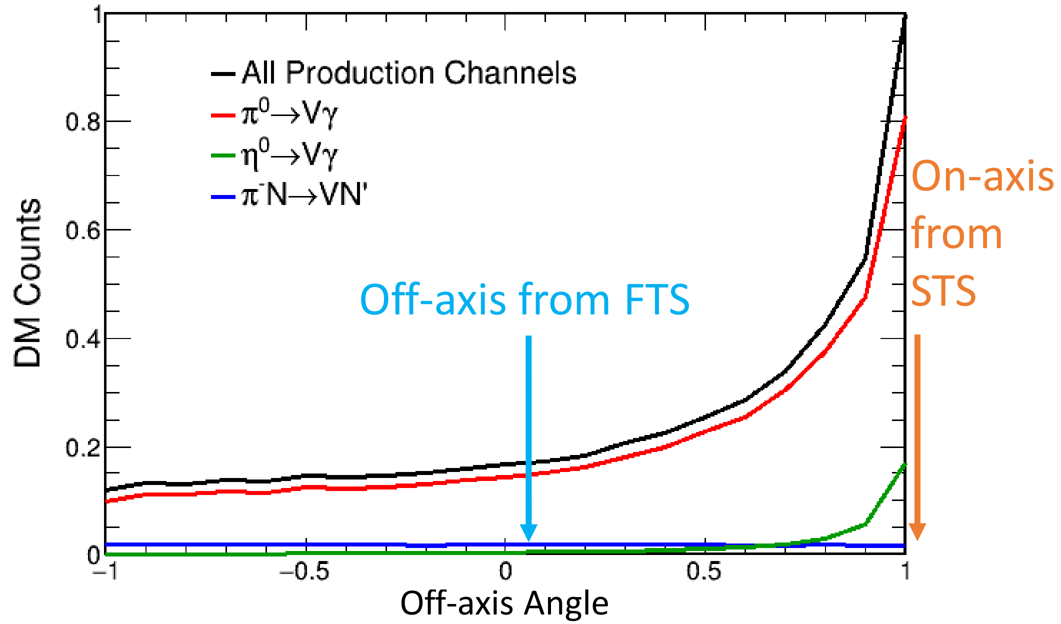
10-ton Detector at Second Target Station



- SNS upgrade plans includes a second target station (STS)
  - Propose a 10 t argon detector at the STS
  - Working with ORNL to plan a new detector hall on-axis with special consideration from neutron shielding
  - During operations, 25% of spills will be delivered to STS / 75% to first target station (FTS)

Utilizing Angular Dependence of DM Flux

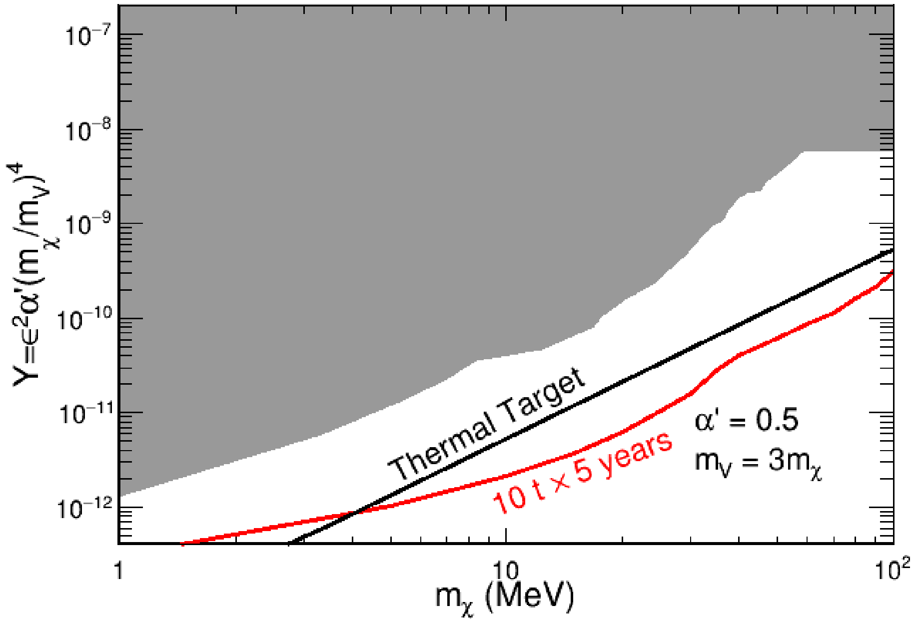


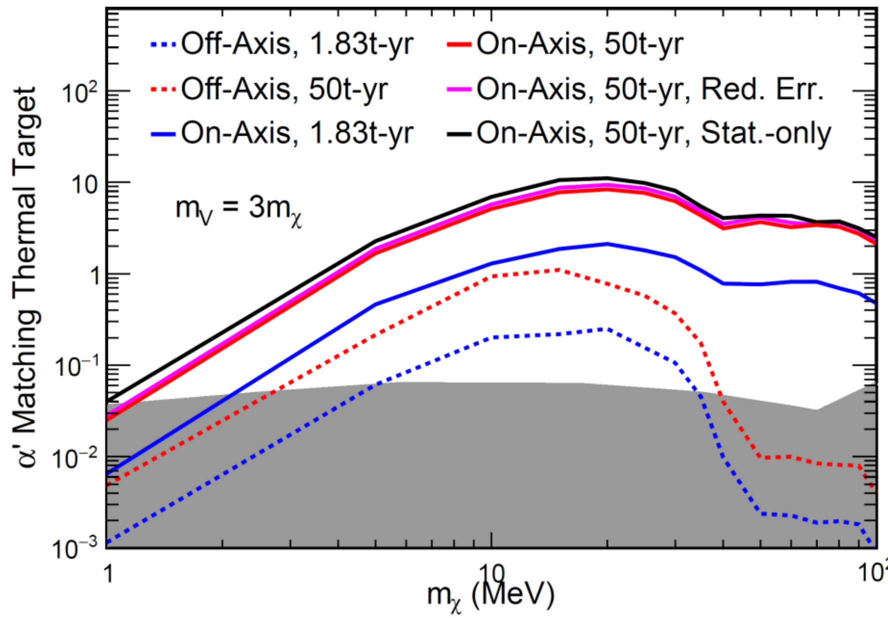


- The neutrino flux in a π-DAR beam is isotropic, but the flux of any dark matter would be boosted
  - Placing detector on-axis at the STS increases S/B
- On-axis at the STS is off-axis from the FTS
  - If a DM-like excess is observed, this angular dependence can be directly tested with the same detector when analyzing data from FTS and STS beam spills separately

DM Sensitivity from COHERENT

Assuming a scalar DM candidate

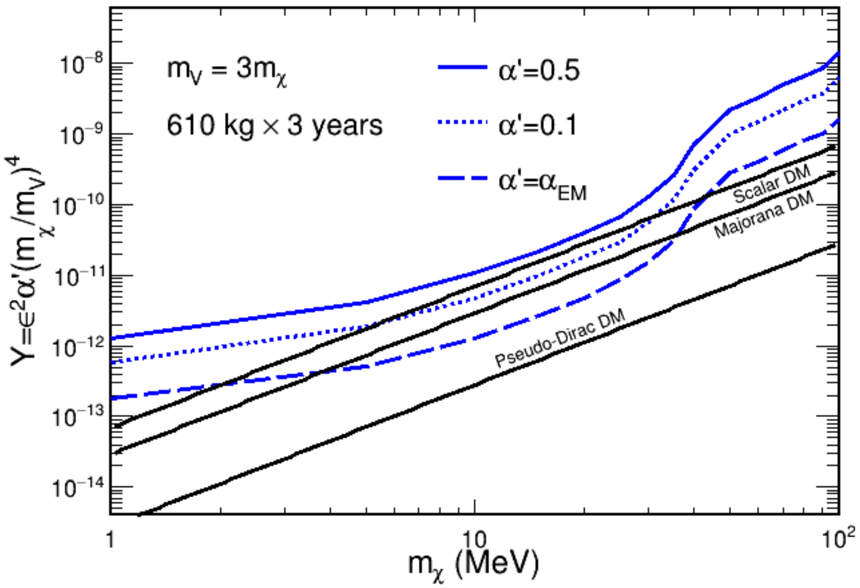




- With a 10 t detector on-axis at the STS we can place very ambitious DM constraints
- Delayed CEvNS mitigate systematic uncertainties, preventing searches from being systematically limited even after 50 t-yr
- The thermal target relating to the cosmological dark matter concentration can be probed for all perturbative $\alpha' < 1$ for $4 < m_\chi < 100$ MeV/c^2

Extras

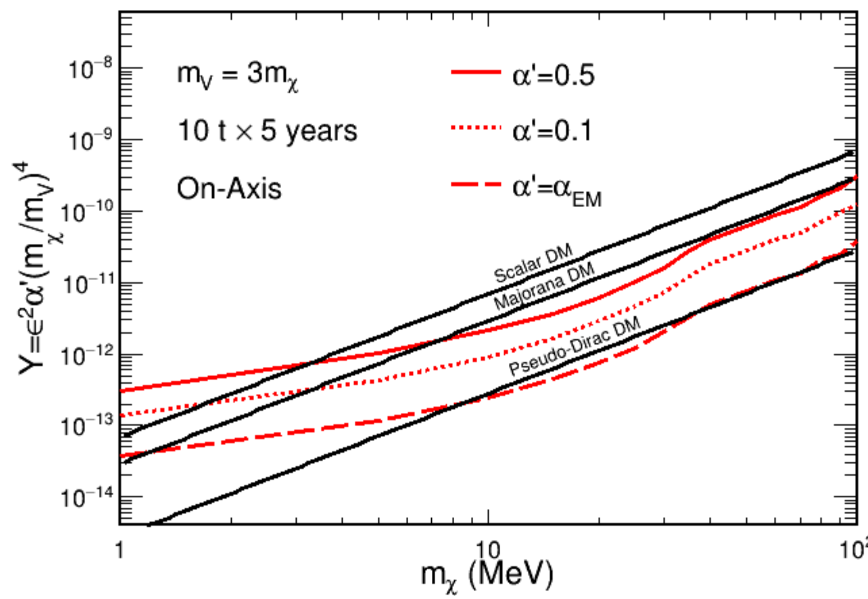
Sensitivity Dependence on DM Couplings



The COHERENT liquid argon detector will test DM consistent with cosmological flux assuming $\alpha' < 0.1$

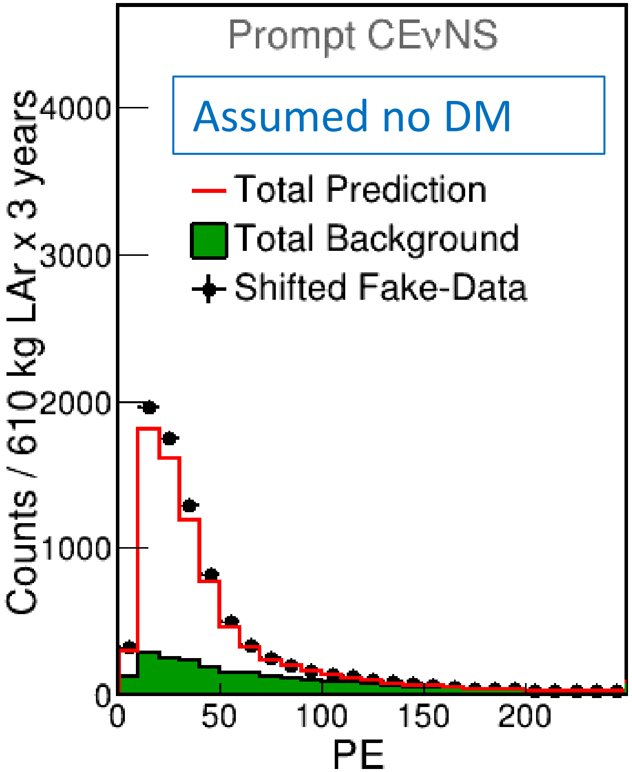
A 10 t on-axis detector would push constraints on scalar and Majorana DM past the perturbative limit

Can test reasonable parameter space for pseudo-Dirac DM



Constraining CEvNS with Timing Info

- Proposed dark matter would be relativistic → the prompt time window is the analysis region of interest
- But … systematic uncertainties stifle our ability to robustly identify signal
- Underestimating the neutrino flux by 10% would give a ≈550 event excess in the ROI that could be mis-interpreted as a dark matter signal

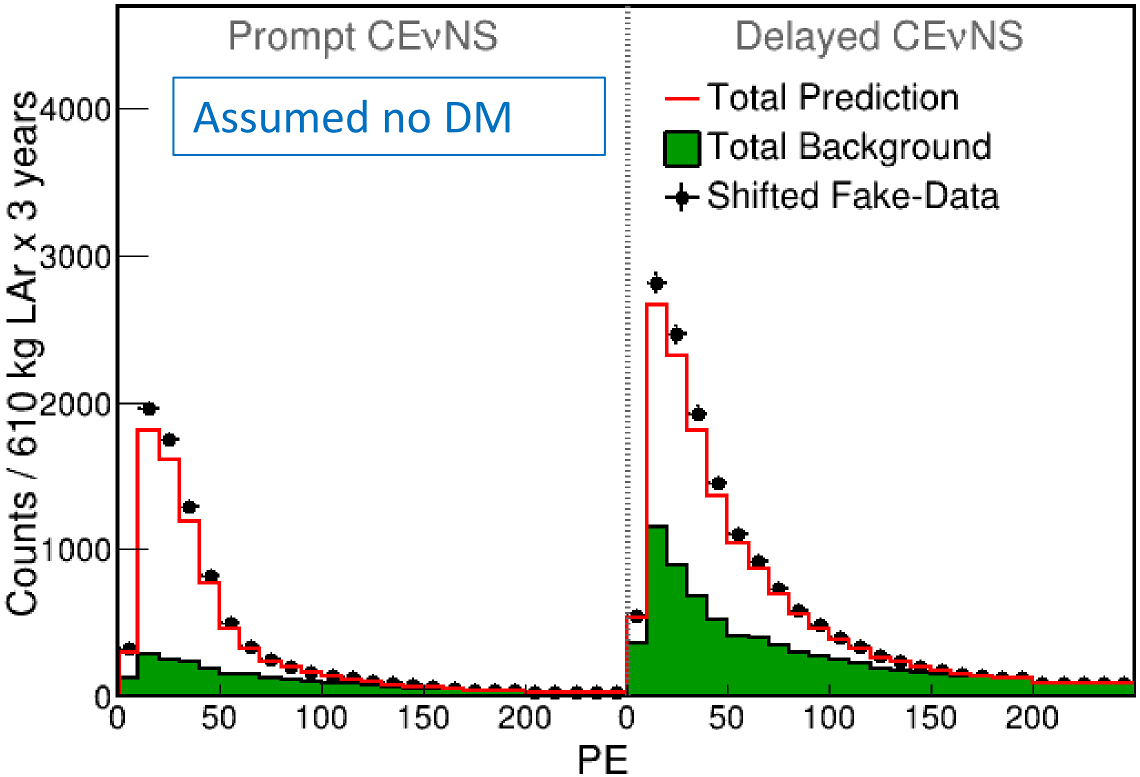


Bkg-Subtracted Counts

	Prompt
Prediction	5469
Fake Data	6016 (+10%)

Constraining CEvNS with Timing Info

- But, an uncertainty on the neutrino flux would affect delayed events too
- Observed data in the delayed timing sideband constrains systematic uncertainties relevant for understanding the CEvNS background in the ROI



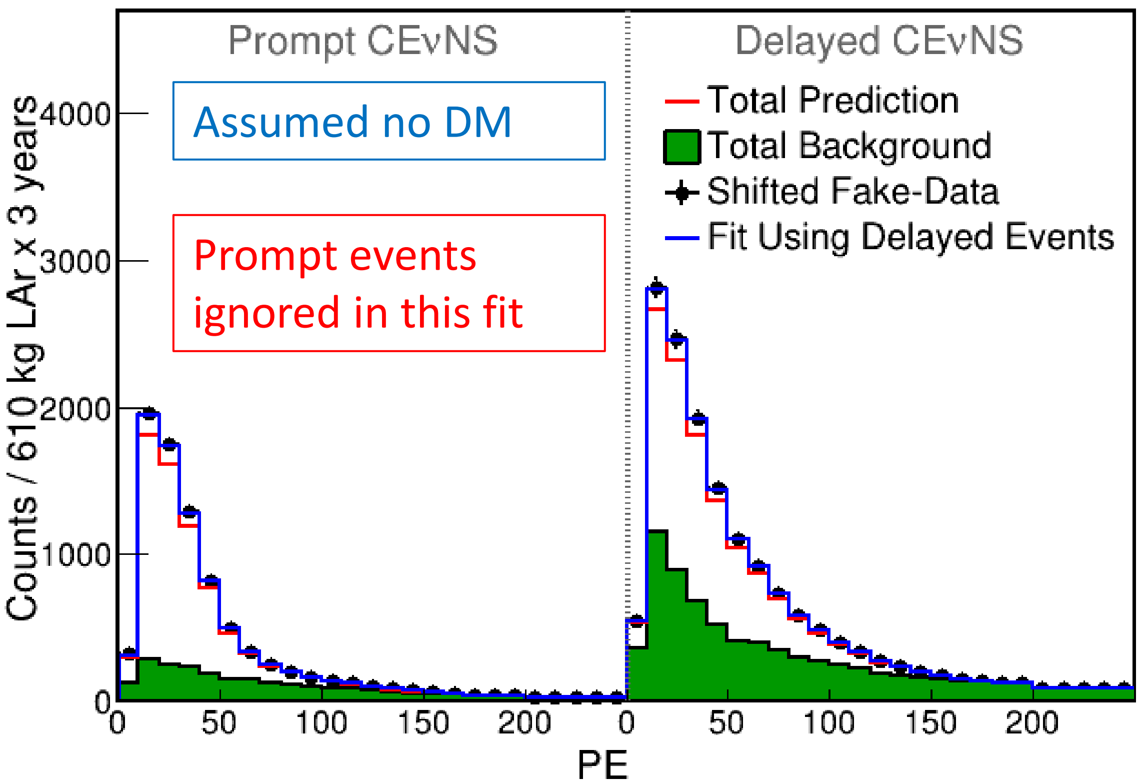
Bkg-Subtracted Counts

	Prompt	Delayed
Prediction	5469	7450
Fake Data	6016 (+10%)	8195 (+10%)

Delayed sideband gives unique information for experiments in π-DAR beams!

Constraining CEvNS with Timing Info

- To understand the power of the constraint, imagine fitting just the delayed sideband to this fake-data with the flux normalization shifted at +10%
- Without analyzing events in the ROI, we've determined we must increase the CEvNS background prediction by 9.3%

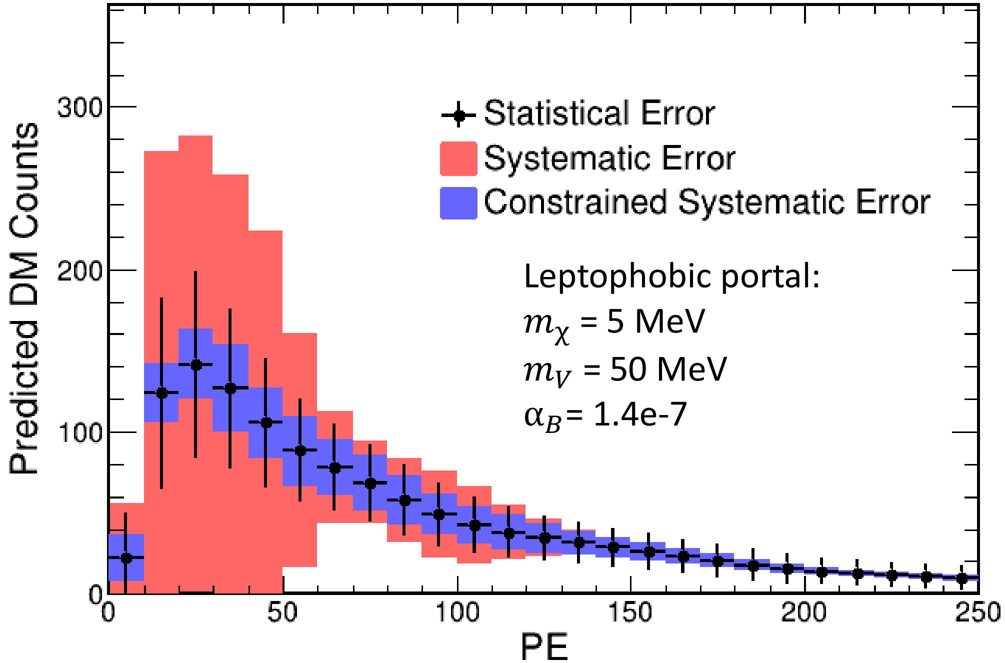


Bkg-Subtracted Counts

	Prompt	Delayed
Prediction	5469	7450
Fake Data	6016 (+10%)	8195 (+10%)
Fit	5980 (+9.3%)	8146 (+9.3%)

Base simulation underestimates the prompt CEvNS bkg by 10%, but a sideband reduces the effect to 0.7%

Error Budget for Identifying DM Scatters



- Without this delayed sideband constraint, a dark matter search would be limited by systematic uncertainties
- Allows for a more detailed understanding of the distinctive recoil energy spectrum expected for DM scatters
- After COHERENT dark matter program, the analysis will be dominated by statistical errors → future paths for DM searches with CEvNS detectors